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Potential yields, yield gaps, and optimal agronomic management practices for rice production systems in different regions of China

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ABSTRACT

Understanding crop potential yields, yield gaps, and optimal agronomic management practices helps in identifying the limiting factors, scope, and ways to achieve sustainable intensified agricultural production. Here, using detailed field trial data collected from 1981 to 2009 at 11 agro-meteorological experimental stations and the crop model CERES–Rice, we investigated changes in potential yields, water- and nitrogen-stressed yields, and yield gaps of rice in the major rice cultivation regions of China during the collection period. We further identified the optimal nitrogen application rate, transplanting date, and cultivar traits for the sustainable intensification of rice production systems in different regions. Owing to climate change, the potential rice yields declined or changed little in the Middle and Lower Reaches of the Yangtze River (MLRYR), while they increased or changed little in the Northeastern China Plain (NECP) during 1981–2009. Rice yield gaps shrank in the major rice production regions because the actual yields increased and approached the potential yields. The average yield gap was 16.0% in the 2000s, with water and nitrogen stresses being the limiting factors in the NECP and water stress being the major limiting factor in the MLRYR. The nitrogen application rate was suggested to be increased by 47.5% and 21.7% for single rice (i.e., rice cultivated in a single season per year) in the NECP and MLRYR, respectively, and increased by 5.2% for early rice (i.e., rice cultivated in the early season in a rice–rice rotation system per year). However, it was suggested to be reduced by 13.1% for late rice (i.e., rice cultivated in the late season in a rice–rice rotation system per year). Early transplanting could increase the yield, while late transplanting could decrease the yield. The impacts were greater for single rice in the NECP and late rice in the MLRYR than for single rice and early rice in the MLRYR. Cultivars with longer growth durations, and greater spikelet numbers and grain weights, could significantly increase the rice yield by 14.8%–45.6%. The optimal cultivars, combined with advancing transplanting by 10 d, could increase rice yields by 29.2%–68.9%. Our findings provide new approaches, important insights, and effective options for the sustainable intensification of rice production systems in different regions of China.

1. Introduction

Global demand for agricultural crops is expected to roughly double by 2050 (Godfray et al., 2010; Tilman et al., 2011); however, limited land and water resources, climate change, and extreme climatic conditions will exacerbate the constraints on food supplies and food security (Ray et al., 2012). Yields for some crops have stagnated in recent decades in particular agricultural regions worldwide owing to changes in climate and agronomic management practices (Brisson et al., 2010; Grassini et al., 2013; Ray et al., 2012; Tao et al., 2015; van Ittersum et al., 2013). The sustainable intensification of crop production systems through nutrient and water management is crucial to increase agricultural production and meet the global food demand in the coming decades (Cassman, 1999; Mueller et al., 2012). Thus, it is necessary to estimate potential yields and yield gaps, the differences between potential and actual yields, for different crops in different regions to determine the production potentials of current cropping systems with the available land and water resources (van Ittersum et al., 2013). The temporal and spatial patterns of potential yields and yield gaps can provide crucial information for the sustainable intensification of crop production systems.

Potential yields and yield gaps have been estimated on global,

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regional, and local levels. At a local level, the yield gap can be estimated by field experiments, yield contests, maximum farmer yields based on surveys, and crop model simulations (Lobell et al., 2009; van Ittersum et al., 2013). Among them, crop modeling is the most reliable method to estimate potential yields and yield gaps because it accounts for interactions among the weather conditions, soils, cultivars, and management practices (van Ittersum et al., 2013; Zhang et al., 2014b). In addition, high quality local data, such as weather and field trial data, are essential for robust estimates of potential yields and yield gaps; however, these are often not available with adequate details for many cropping systems. Different approaches, crop models, and input data can result in different estimates of potential yields and yield gaps (Tao et al., 2015), and these estimates for rice production systems in different regions of China have been inconsistent and inconclusive to date (Chen et al., 2017).

China is a top producer and consumer of rice, producing a third of the rice in the world. Rice is the staple food for > 65% of the Chinese people (Zhang et al., 2005). However, rice production has been facing challenges, including a decline in arable land, increasing water scarcity, global climate change, and labor shortages (Peng et al., 2009). Decreases in solar radiation and increases in extreme high temperatures have had notable impacts on rice productivity in recent decades, although climate warming increased the growing degree-days for rice production (Tao et al., 2013; Zhang et al., 2014a, b). In addition, rice production in China faces other challenges, such as the overuse of fertilizers and pesticides, breakdown of the irrigation infrastructure, and oversimplified crop management practices (Peng et al., 2009). Therefore, it is essential to investigate the potential yields and yield gaps, and develop optimal cultivars and agronomic management practices to accelerate the sustainable intensification of rice production systems in different regions of China (Cui et al., 2018).

Previous studies have investigated rice potential yields and yield gaps, cultivars, transplanting dates, fertilization regimens, and irrigation separately, although they are closely correlated and should be investigated in the context of genotype, environment, and management interactions. Furthermore, the long-term changes in potential yields and yield gaps, and particularly the optimal agronomic management practices, have rarely been investigated systematically for rice production systems in different regions based on detailed long-term trial data. In this study, based on valuable long-term field trial data from 1981 to 2009 at 11 agro-meteorological experimental stations across the major rice production regions in China, together with the crop model CERES–Rice, we tried to determine a set of optimal agronomic management practices for intensified sustainable agricultural production through the optimization of interactions among genotype, environment, and management practices. We aimed to 1) investigate the changes in potential yields, water- and nitrogen (N)-stressed yields, and yield gaps of rice in the major rice cultivation regions of China from 1981 to 2009; 2) investigate the impacts of N stress and water stress on yield; 3) optimize N fertilization application rates, transplanting dates, and cultivars to achieve the sustainable intensification of rice production systems in different regions of China.

2. Material and methods

2.1. Experimental stations and data

Rice crop zoning in China was based on climate and soil conditions, rice cultivar characteristics and their distributions in different areas of China (Mei et al., 1988). Based on these zones, we selected 11 representative agro-meteorological experimental stations with long-term field trial data from 11 provinces. They were located in the major rice cultivation regions of China, the Northeastern China Plain (NECP) and the Middle and Lower Reaches of the Yangtze River (MLRYR) (Fig. 1). The stations in the NECP were Wuchang (WC), Yanbian (YB), and Xinbin (XB), where single rice cultivation was the dominant cropping system. The stations in the MLRYR were Ganyu (GY), Mianyang (MY), and Wanxian (WX), where the dominant cropping system was the rotation between wheat and rice, and Tongcheng (TC), Xiaogan (XG), Jinhua (JH), Changde (CD), and Zhangshu (ZS), where the dominant cropping system was double rice cultivation. Most of these experimental sites were selected from pieces of farmers' land; therefore, the agronomic management practices and soil conditions in the experimental fields could be considered the same as the farmers' fields. They reflected the management practices and soil conditions in the rice cultivation regions where the stations were located. Moreover, yields and yield variations at the experimental stations were generally consistent with those at the county scale over the past 29 years (Fig. S1; Fig. S2). Therefore, the observed yields at the experimental stations were representative of the general characteristics of yields in their surrounding areas. The details of the stations are presented in Table 1.

The weather data used in this study included daily solar radiation (MJ/m^2), daily maximum temperature (°C), daily minimum temperature (°C), and daily precipitation (mm) from 1981 to 2009. They were obtained from the Chinese Meteorological Data Service Center (http://data.cma.cn/en). Daily solar radiation was calculated using the Angstrom-Prescott equation (Angstrom, 1924; Prescott, 1940) with sunshine hour data.

Rice trial data at the experimental stations from 1981 to 2009 were obtained from the Chinese Meteorological Administration. These data included cultivars, phenology, yields, and fertilization management practices. In the experimental records, the yields for the counties near the stations were also documented for each year. Soil profile data at the selected stations were obtained from local experimental stations and the China Soil Database (http://vdb3.soil.csdb.cn/).

2.2. CERES–Rice model

The CERES–Rice model in Decision Support System for Agro-technology Transfer version 4.5 (Jones et al., 2003) was used to simulate the growth, development, and grain yield of rice from 1981 to 2009. The CERES–Rice model is an extensively used process-oriented crop model worldwide (Kim et al., 2013; Tao et al., 2008a; Xiong et al., 2014). The model considers the effects of climate, cultivar, fertilizer, and soil, and can simulate rice growth, as well as soil water and N dynamics in daily steps. It has eight crop cultivar genetic parameters to describe the phenology and yield characteristics of specific genotypes. The definitions of the genetic parameters and the range of each parameter derived from all the rice cultivars existing in the CERES–Rice model are listed in Table 2. Detailed descriptions of the CERES–Rice model are available at the website: http://dssat.net/.

At each of the 11 agro-meteorological experimental stations, the observed heading dates, maturity dates, and yield data were used to calibrate and validate the CERES–Rice model. The crop cultivar was usually updated every 3 to 5 years in the study regions. As a consequence, the field trial data that recorded the typical rice cultivars and typical managements were selected from 2005 to 2009. The data in the first one or two years were used to calibrate the model, and the rest of the data were used to validate the model. The N application rate was 100–160 kg/ ha for single rice in the NECP, 120–150 kg/ ha for single rice in the MLRYR, 120–190 kg/ ha for early rice in the MLRYR, and 140–200 kg/ ha for late rice in the MLRYR. In this study, irrigation was set automatically in the model calibration, i.e., irrigating 10-mm water when the water level was < 50% of capacity at a 30-cm depth. We used the normalized root-mean-square error (%) and the D_{index} (Timsina and Humphreys, 2006; Willmott, 1982) to test the performance of the model. The validated results demonstrated a good consistency between simulated and observed crop phenology and grain yield (Fig. S3), which indicated that the validated CERES–Rice model could be accepted to simulate rice development, growth, and grain formation in the study regions.

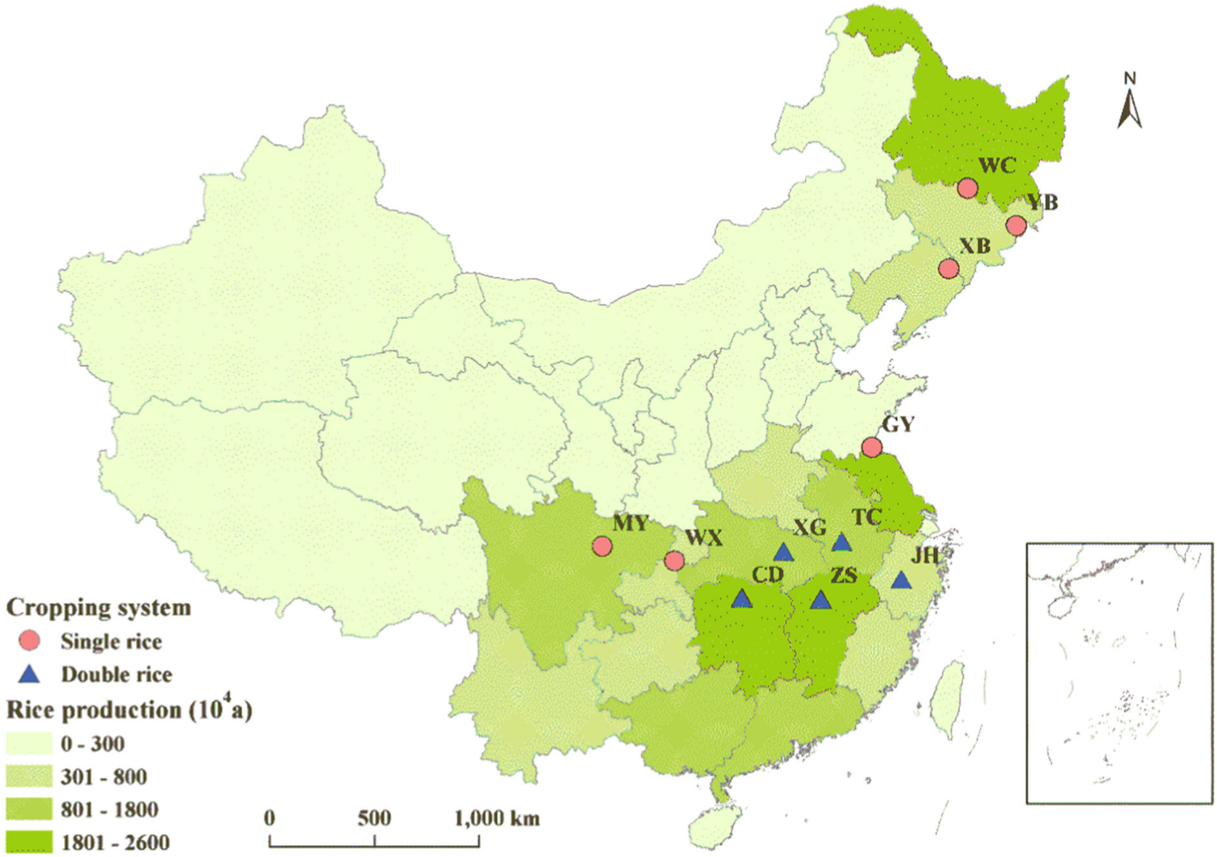

Fig. 1. Locations of the study sites.

2.3. Investigation of potential yields, yield gaps, and yield limiting factors

Potential yield in this study was defined as the yield of an adapted cultivar grown in an ideal environment without nutrient stress or water stress (Lobell et al., 2009). The validated CERES–Rice model was applied to simulate potential yields (Y_P) during 1981–2009 at each of the 11 stations. Yield gap (Y_G) was calculated as the difference between the simulated potential yield (Y_P) and the observed yield (Y_O) in each year:

$$Y_G = Y_P - Y_O \quad (1)$$

Y_P was the simulated potential yield under sufficient water and N conditions. The impacts of pests and diseases on rice yields were not taken into account in this study. Therefore, the difference between Y_P and Y_O was mainly affected by water and nutrient stresses. Rice is mainly cultivated with irrigation across the major production regions in China. Even so, rice suffers from droughts when irrigation water is not available in some drought years or with inadequate irrigation. To investigate the effects of water and N stress on the potential yields, two simulation experiments were performed to determine rice yields during 1981–2009 in different regions of China (Table 3).

Y_{PW} indicates the water-limited potential yield under sufficient N but water-stress (derived from irrigation or the ability of the roots to absorb water) conditions. The water- and N-limited yield (Y_{PWN}) was that under both water- and N-stress (derived from field managements or the ability of the roots to absorb water and N) conditions. Y_{PW} indicates automatic irrigation without considering N stress in the model. Y_{PWN} indicates automatic irrigation and the N application rate in the experimental records.

Yield gaps caused by water stress (G_W), N stress (G_N), and both water and N stress (G_{WN}), were calculated as follows:

$$G_W = (Y_P - Y_{PW})/Y_P \times 100\%, \quad (2)$$

$$G_N = (Y_{PW} - Y_{PWN})/Y_P \times 100\% \text{and} \quad (3)$$

$$G_{WN} = (Y_P - Y_{PWN})/Y_P \times 100\%, \text{ respectively.} \quad (4)$$

2.4. Rice cultivar optimization

In this study, the traits of high-yielding cultivars were identified by optimizing the cultivars' genetic parameters in the CERES–Rice model. In total, 3 of the 11 representative stations were selected to do this. They were WC with single rice cultivated (WC_S) in the NECP, GY with a rotation between wheat and rice (GY_S) in the MLRYR, and CD with a rotation between early rice (CD_E) and late rice (CD_L) in the MLRYR. The optimization procedures included two steps. First, a sensitivity analysis of the cultivars' genetic parameters in the CERES–Rice model was performed to understand the sensitivity of rice yield to each of the eight cultivar parameters. To do so, the range of values for each parameter (X) was divided into five equal intervals from the minimum (X_{min}) to the maximum (X_{max}) [i.e., X_{min} to $X_{min} + 1/5(X_{max} - X_{min})$, $X_{min} + 1/5(X_{max} - X_{min})$ to $X_{min} + 2/5(X_{max} - X_{min})$, ……, $X_{min} + 4/5(X_{max} - X_{min})$ to X_{max}], according to the parameter range shown in Table 2. The median of each interval was selected as the parameter value for the interval. Thus, there were five values [i.e., $X_1 = X_{min} + 1/10(X_{max} - X_{min})$, $X_2 = X_{min} + 3/10(X_{max} - X_{min})$, $X_3 = X_{min} + 5/10(X_{max} - X_{min})$, $X_4 = X_{min} + 7/10(X_{max} - X_{min})$, $X_5 = X_{min} + 9/10(X_{max} - X_{min})$] for each parameter, representing five different levels of the parameter (i.e., cultivar trait). By allowing one target parameter to change among its five different levels (from X_1 to X_5), while keeping the other seven parameters unchanged, five sets of cultivar parameters were derived. Then, the five sets of cultivar parameters were used to simulate rice growth and yield under current agronomic management practices during 1981–2009 to investigate the sensitivity of yield to the target parameter. Second, the cultivars' genetic parameters were

Table 1
Information on the climate and soil for the 11 representative stations.

Stations	WC_S[a]	YB_S	XB_S	GY_S	MY_S	WX_S	TC_E	TC_L	XG_E	XG_L	JH_E	JH_L	CD_E	CD_L	ZS_E	ZS_L
Latitude (°N)	44.9	42.9	41.7	34.8	31.5	30.8	31.1	31.1	30.9	30.9	29.1	29.1	29.1	29.1	28.7	28.7
Longitude (°E)	127.2	129.5	125.1	119.1	104.7	108.4	117.0	117.0	114.0	114.0	119.7	119.7	111.7	111.7	115.6	115.6
Altitude (m)	194.6	176.8	328.4	3.3	522.7	186.7	85.4	85.4	25.3	25.3	62.6	62.6	35.0	35.0	30.4	30.4
Annual mean temperature (°C)	3.4	5.8	4.8	13.2	16.0	17.7	16.0	16.0	15.8	15.8	17.5	17.5	16.7	16.7	17.8	17.8
Typical cropping system	Single rice	Single rice	Single rice	Wheat- rice	Wheat- rice	Wheat- rice	Early rice	Late rice	Early rice	Late rice	Early rice	Late rice	Early rice	Late rice	Early rice	Late rice
Soil texture	Loam	Clay	Silty loam	Loam	Loam	Silty loam	Loam	Loam	Loam	Loam	Loam	Loam	Clay loam	Clay loam	Silty loam	Silty loam
Organic matter (%)	4.84	1.62	1.82	2.15	2.33	2.36	2.15	2.15	2.04	2.04	2.29	2.29	3.16	3.16	2.58	2.58
Total N (%)	0.24	0.09	0.09	0.13	0.14	0.15	0.13	0.13	0.11	0.11	0.14	0.14	0.17	0.17	0.14	0.14

[a] The subscript represents the cropping system; single rice, S; early rice, E; and late rice, L.

Table 2
Genetic parameters and their ranges in the CERES–Rice model of Decision Support System for Agro-technology Transfer, v. 4.5.

Genetic parameters	Definition (units)	Range
P_1	Time period for basic vegetative phase (growing degree days [GDD] in °C above base 9 °C)	100–880
P_2R	Photoperiod sensitivity parameter (GDD in °C)	5–300
P_5	Time period for grain filling phase (GDD in °C above base 9 °C)	200–580
P_2O	Critical photoperiod (hours)	10–13.5
G_1	Potential spikelet number coefficient	38–78
G_2	Potential single grain weight (g)	0.02–0.03
G_3	Tillering coefficient	0.3–1.1
G_4	Temperature tolerance coefficient	0.8–1.25

Table 3
Settings of simulation experiments used to evaluate the effects of water and nitrogen (N) stresses on rice yield gaps.

Scenario	Climate	Cultivar	Transplanting date	Water-stress	N-stress
Y_P	1981–2009	Fixed	Fixed	No	No
Y_{PW}	1981–2009	Fixed	Fixed	Yes	No
Y_{PWN}	1981–2009	Fixed	Fixed	Yes	Yes

optimized to identify high-yielding traits. Based on the sensitivity analysis, if one parameter had a linear impact on yield at all four stations, then the parameter value that produced the greatest yield was adopted as the optimal value for the parameter. Then, the five values (X_1, X_2, X_3, X_4 and X_5) for each of the other parameters were randomly combined, resulting in 5^n (n being the number of selected parameters) sets of cultivar genetic parameters. Afterward, all 5^n sets of cultivar parameters were used to simulate rice yields under current agronomic management practices during 1981–2009. Some basic principles were applied in designing the simulation scenarios. For example, the maturity date of early rice should be before the transplanting date of late rice. The cultivars having the top five sets of genetic parameters that resulted in the greatest yields were selected as the optimal cultivars for the stations. The application of the method is described using actual parameters in Section 3.4.

2.5. Agronomic management optimization

For each of the 11 stations, we applied the validated CERES–Rice model to simulate rice yields during 1981–2009 under different fertilization application rates and transplanting dates. We further investigated the impacts of different fertilization application rates and transplanting dates on rice growth and yield. The optimal N application rate and optimal transplanting date were then identified.

To identify the optimal N application rate, we simulated rice yield and calculated nitrogen use efficiency (NUE) during 1981–2009 at each of the 11 stations, with the N application rate ranging from 0 to 300 kg/ha in a 30-kg/ha gradient. The N application rate resulting in the greater rice yield and greater NUE was identified as the optimal N application rate. The NUE was calculated as follows:

$$\mathrm{NUE} = \mathit{Yield}/\mathit{N\ application\ rate}. \quad (5)$$

In addition, at each of the 11 stations, we simulated rice growth and yield with different transplanting dates during 1981–2009. Based on the observed transplanting date, we set a transplanting window from 10 d in advance to 10 d after the observed transplanting date, with a 2-d gradient. The length of the transplanting window was determined based on the generally small shifts in transplanting dates during 1981–2009 at these stations. We then compared the simulated rice yields at different transplanting dates with the observed yields at the current transplanting dates. The impact of different transplanting dates on rice yield

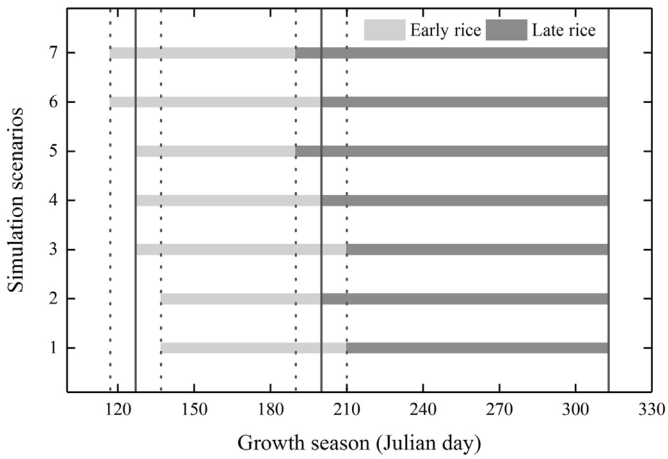

Fig. 2. Simulation scenarios to optimize the interactions between transplanting date and cultivar for double rice cropping system (early and late rice rotations). The vertical solid line indicates the current boundary of the growing season. The nearby two dotted lines represent the range of the transplant date (± 10 d).

was investigated, and the optimal transplanting date was then identified for the current cultivar at each of the 11 stations.

To explore the interactions between transplanting date and cultivar, we simulated the yields of all the 5^n cultivars described in Section 2.4 with three different transplanting dates: current, 10 d earlier, and 10 d later. For the double rice rotation (early and late rice rotation), the system was taken as a whole to explore the optimal transplanting date and optimal cultivar. With early rice transplanted at the current transplanting date, 10 d earlier, and 10 d later, the transplanting date of the late rice could change accordingly or was not changed, which led to different combinations of early and late rice growth seasons. The principle that the growth season was not changed by > 10 d was used in the simulations. As a consequence, there were seven simulation scenarios, as shown in Fig. 2. For different transplanting dates, the top five high-yielding cultivars from the 5^n cultivars were selected, and the optimal transplanting dates and rice growth durations were subsequently determined.

3. Results

3.1. Changes in rice potential yields and yield gaps from 1981 to 2009

Changes in the potential yields, observed yields and yield gaps from 1981 to 2009 at each of the 11 stations in the NECP and the MLRYR are

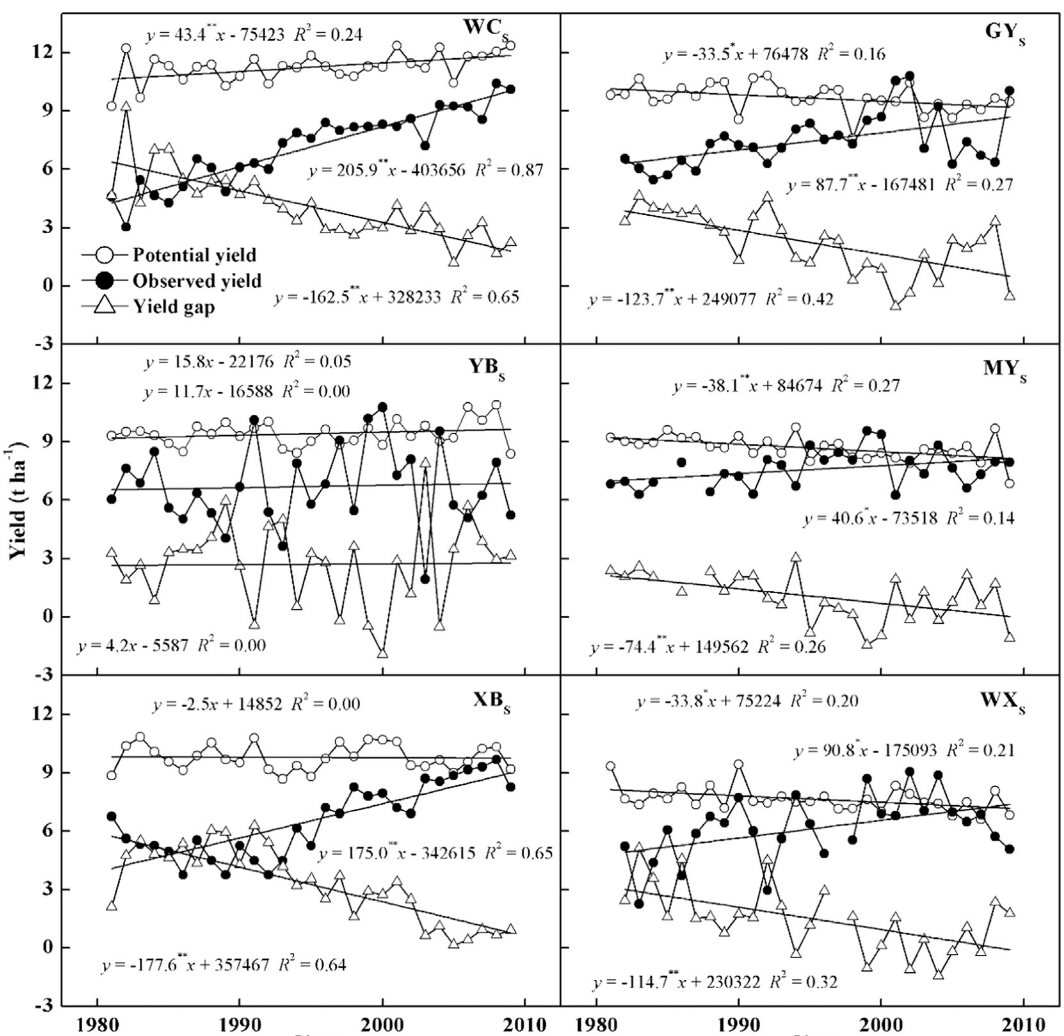

Fig. 3. Time series of potential yields, observed yields, and yield gaps for single rice at three stations in the NECP (WC, YB, and XB) and three stations in the MLRYR (GY, MY, and WX). The subscript 'S' represents single rice cultivation.

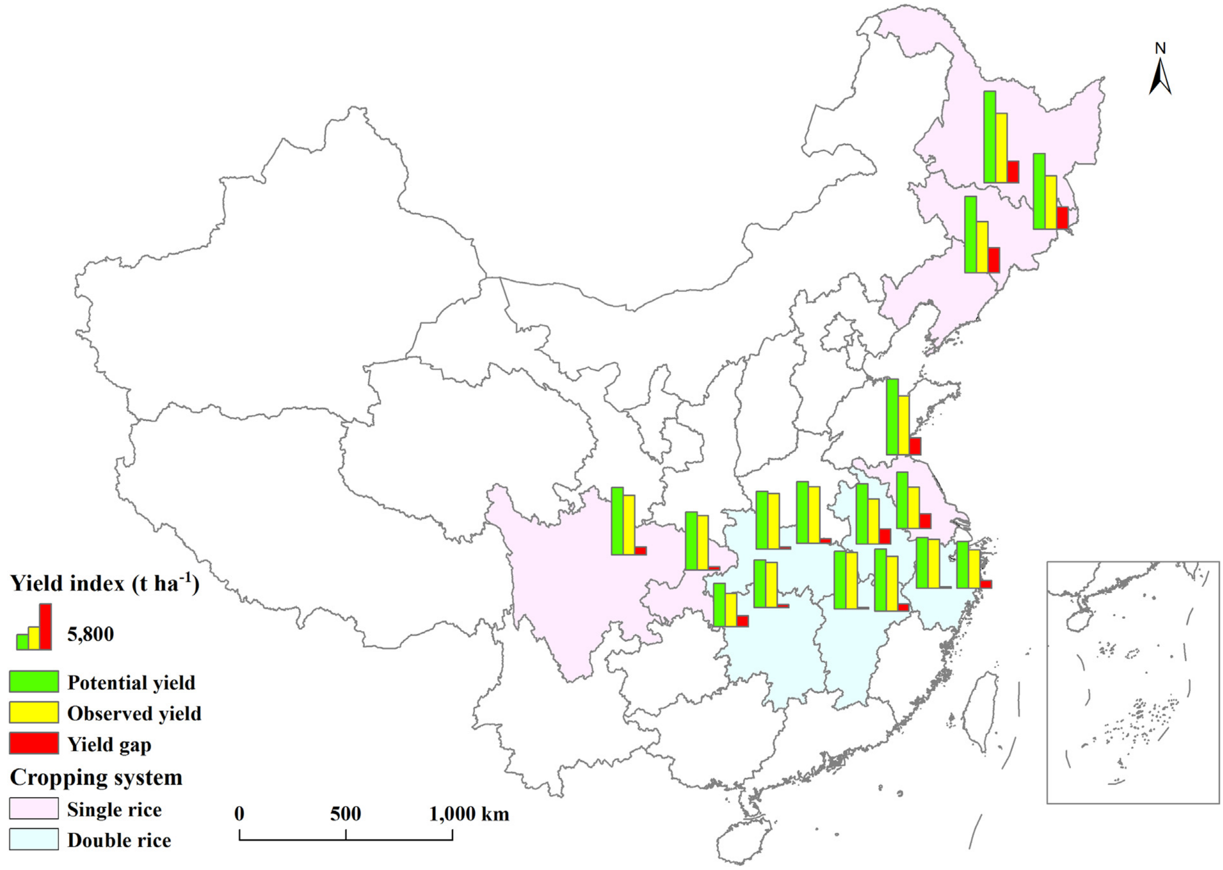

Fig. 4. Spatial patterns of potential yields, observed yields and yield gaps of rice at each of the 11 agricultural meteorological stations in the 2000s (2000–2009).

shown in Fig. 3. Of the stations in the NECP with single rice cultivation, the potential yield in WC had an increasing trend ($p < .01$) during the period, on average, of 43.4 kg/ha per year. Trends in the potential yields at YB and XB were not significant. The observed yields at WC and XB increased significantly ($p < .01$) by 175.0 to 205.9 kg/ha per year, respectively, but there was little change at YB. As a result, the yield gaps shrank significantly at WC and XB during the period, by 162.5 to 177.6 kg/ha per year, respectively, but increased insignificantly at YB (Fig. 3). At the three stations with single rice cultivation in the MLRYR, from 1981 to 2009, the potential yields declined significantly ($p < .01$) on average by 33.5 to 38.1 kg/ha per year. At the same time, the observed rice yields at the three stations significantly increased by 40.6 to 90.8 kg/ha per year. As a result, the yield gaps at the three stations decreased significantly by 74.4 to 123.7 kg/ha per year (Fig. 3).

For early rice in the MLRYR, the potential yields declined significantly, while the observed yields increased significantly at TC, XG, and ZS from 1981 to 2009 (Fig. S4). The potential and observed yields at JH and CD showed limited changes. At TC, XG, and ZS, the yield gaps shrank significantly by 53.5, 138.1, and 114.1 kg/ha per year, respectively. The yield gaps at JH and CD showed limited changes.

For late rice, the potential yields declined significantly by 55.0 and 61.3 kg/ha per year at JH and ZS. The observed yields at TC, XG, and CD increased notably by 85.0, 121.8, and 122.3 kg/ha per year, respectively. As a result, the yield gaps shrank significantly at TC, XG, and ZS by 94.4, 147.0, and 148.8 kg/ha per year, respectively, from 1981 to 2009.

3.2. Spatial patterns of potential yields, observed yields, and yield gaps

The spatial patterns of potential yields, observed yields, and yield gaps at each of the 11 agricultural meteorological stations in the 2000s (2000–2009) are shown in Fig. 4. The averages of the observed yields were 7410 kg/ha for single rice in the NECP, 7350 kg/ha for single rice in the MLRYR, 6448 kg/ha for late rice in the MLRYR, and 5716 kg/ha for early rice in the MLRYR (Fig. 4). The potential yields changed remarkably across the cultivation regions, with averages of 10,378 kg/ha for single rice in the NECP, 8561 kg/ha for single rice in the MLRYR, 7103 kg/ha for late rice in the MLRYR, and 6803 kg/ha for early rice in the MLRYR. In general, the potential yields increased as the latitude increased. As a result of shorter growth durations, the potential yields for early rice and late rice were lower than those for single rice. The yield gap was 16.0% on average, with 28.9% for single rice in the NECP, 16.8% for early rice in the MLRYR, 13.4% for single rice in the MLRYR, and 8.9% for late rice in the MLRYR. The yield gaps in the NECP were significantly greater than those in the MLRYR (Fig. 4).

3.3. Water- and N-stressed yields and the related yield gaps

At the three stations with single rice cultivation in the NECP, the yield gaps caused by N and water stresses were 10.7% and 7.2%, respectively (Fig. 5). The major limiting factors were different among the three stations. At WC, yield was limited by both N and water stresses. At YB, the impact of N stress on yield was greater than that of water stress. At XB, yield was mainly limited by water stress (Fig. 5). At the three stations with single rice cultivation in the MLRYR, the yield gaps caused by N and water stresses were 3.7% and 7.3%, respectively. At GY, the impact of N stress on yield was greater than that of water stress. At MY and WX, yields were mainly restricted by water stress (Fig. 5). For early rice at the five stations with double rice cultivation in the MLRYR, the yield gaps caused by N and water stresses were 1.2% and 9.8%, respectively. At all the stations, the impact of water stress on yield was greater than that of N stress. For the five late rice stations in the MLRYR, the yield gap of 6.9% was mainly caused by water stress (Fig. 5).

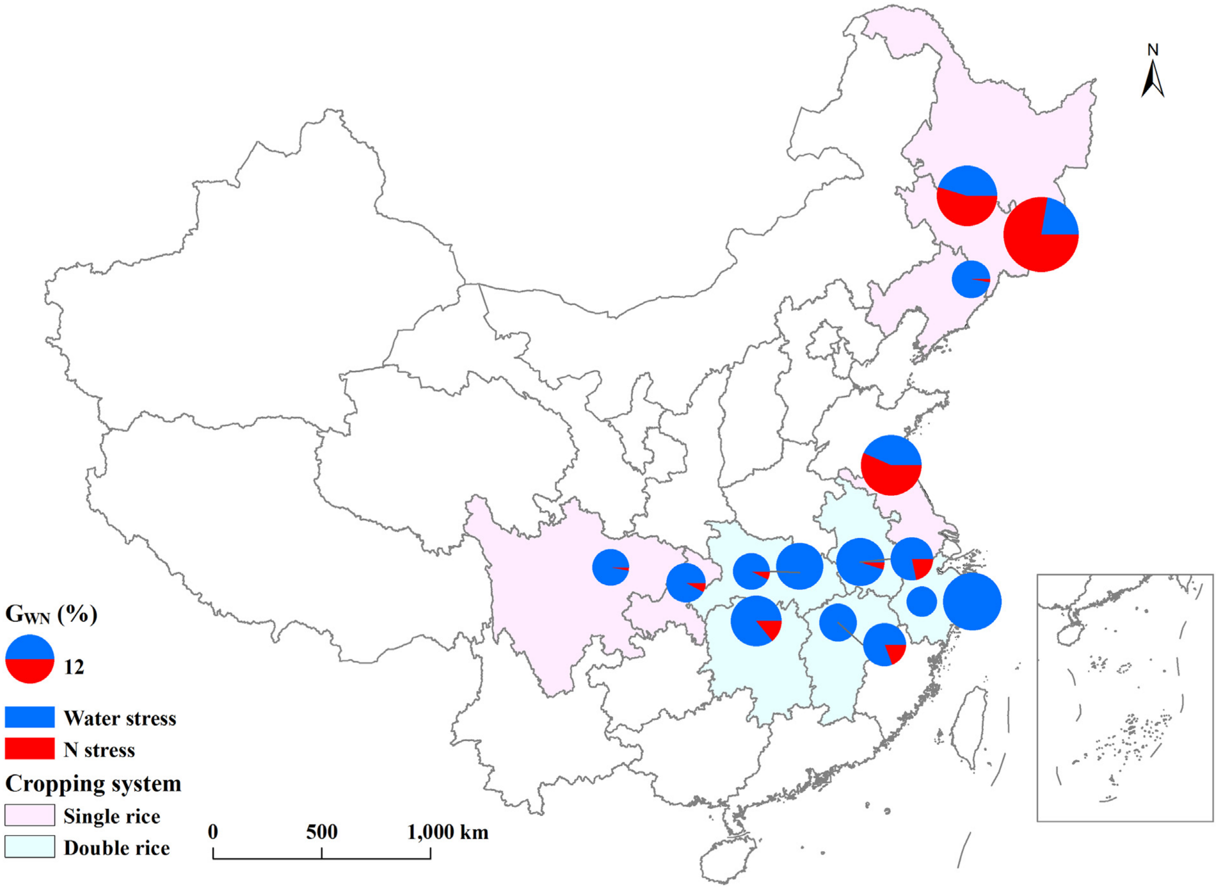

Fig. 5. Spatial patterns of rice yield gaps caused by water stress, N stress, and both water and N stress at all the stations in the 2000s (2000–2009).

3.4. Rice cultivar optimization

The sensitivity of rice yield to each genetic parameter is shown in Fig. 6. With increases in P1, P2R, P5, G1, and G2 values, especially P1 and P2R, rice yields could increase. By contrast, with increases in P2O and G3, rice yields could decrease. Yield was not sensitive to G4 (Fig. 6). For the current cultivars, the optimized direction and extent of individual genetic traits could be deduced. For example, for the current cultivar at WC, P1 could be increased by up to 490 to promote rice yield.

With increases in G1 and G2 values, yields increased correspondingly. Thus, for the integrative optimization of cultivar parameters, the maximum parameter value was taken as the optimal value for G1 and G2, i.e. 77.7 and 0.03, respectively. Yield was slightly sensitive to G4, and the original value of 1.0 was taken as the optimal value for G4. For each of the remaining five parameters, the values were selected to generate random combinations, resulting in 5^5 (3125) sets of parameters for each station. These 3125 sets of perturbed parameters were used to simulate rice growth and yield for the period of 1981–2009 under current agronomic management practices. The five sets of parameters that resulted in the greatest yield for each station are shown in Table S1. At WC, the traits of the high-yielding cultivars were characterized by lower P1, lower G3, and higher P5 in comparison with the current cultivar (Fig. 6). At GY, the traits of the high-yielding cultivars were mainly characterized by higher P1 and lower G3. At CD, the traits of the high-yielding cultivars for early rice were mainly characterized by lower G3; while the traits for the high-yielding cultivars of late rice were mainly characterized by higher P1 and G3 values. There was no obvious preference for P2R or P2O because the two parameters jointly describe photoperiod sensitivity. In addition, the cultivars with greater G1 and G2 values could improve yields at all three stations.

We summarized the phenology and yield changes of the top five high-yielding cultivars compared with the current cultivars at three stations (Fig. 7). Using the optimal cultivars, yields could significantly increase from 14.8% to 45.6% and the whole-growth duration was significantly prolonged from 4.1 to 13.3 d, except for early rice at CD. At WC, the optimal cultivars could result in higher yields by shortening the vegetative growth period and prolonging the reproductive growth period. At GY, optimal cultivars could result in greater yields by prolonging the vegetative growth period. At CD, cultivars of early rice could not result in greater yields through the prolonged growth period because the growth period was limited by the transplanting date of the late rice. Late rice cultivars at CD could result in greater yields by prolonging both the vegetative and reproductive growth periods.

3.5. Agronomic management practices optimization

3.5.1. Optimal NUE at each station

Responses of rice yields and NUE to different N application rates for single rice in the NECP and in the MLRYR are shown in Fig. 8. With increases in the N application rate, rice yields first increased and then plateaued. Additionally, the NUE declined rapidly and was then maintained at a low level, after a certain N application rate. After reaching a certain N application rate, rice yield did not increase or increased slightly. The N application rate that resulted in a plateau level at a high yield was identified as the optimal N application rate. In the NECP, the optimal N application rates at WC, YB, and XB were 150, 180, and 180 kg/ha, respectively (Fig. 8), which were ~47.5% greater than current N application rates at these experimental stations. In the MLRYR, the optimal N application rate for single rice at GY, MY, and WX were 210, 150, and 150 kg/ha, respectively, which were ~21.7% greater than the current N application rates (Fig. 8).

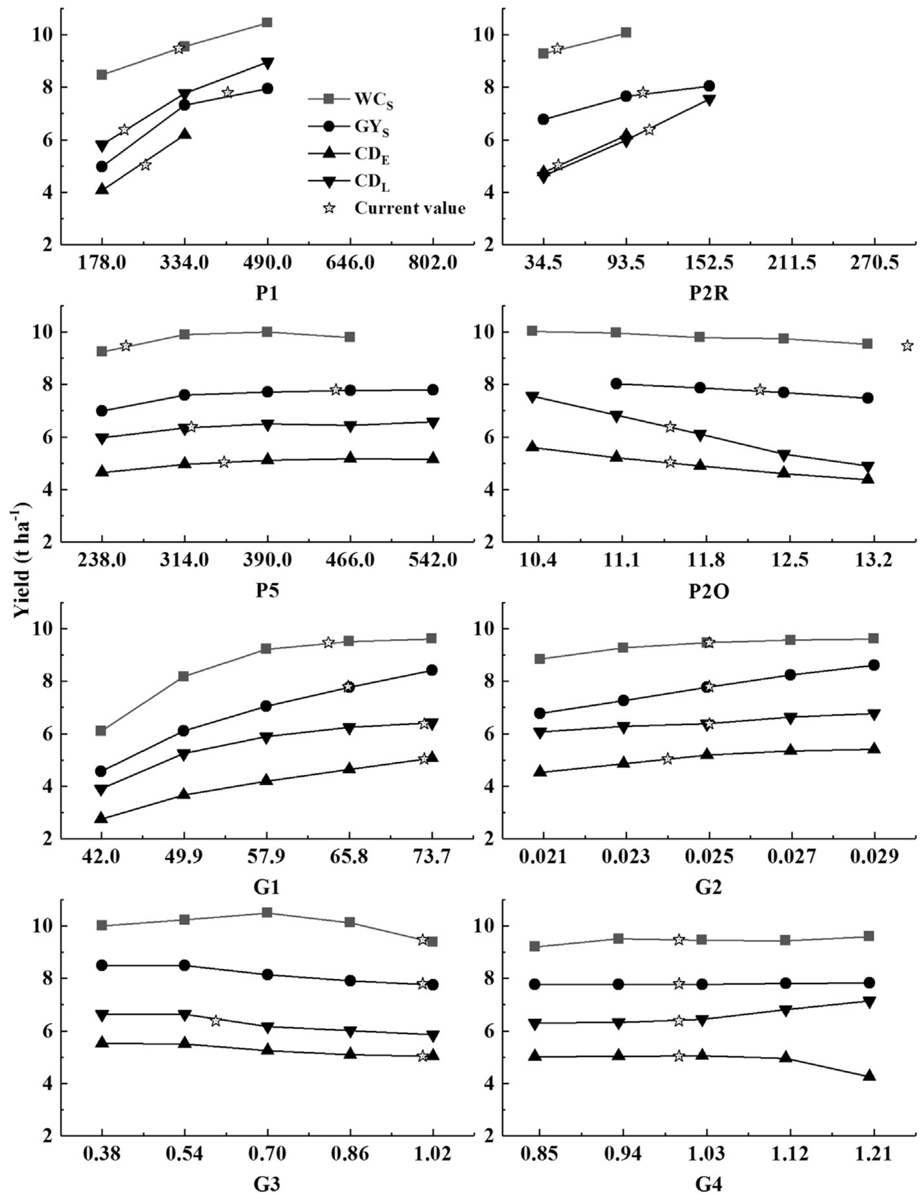

Fig. 6. Sensitivity of rice yield to each specific genetic parameter at three stations. ☆ represents the corresponding parameter value for the current cultivars. There are missing values in the first four panels because rice did not mature in a reasonable time window with increases in P1, P2R, P5, and P2O. The subscripts in legends represent the cropping system; single rice, S; early rice, E; and late rice, L.

The optimal N application rates for early rice in the MLRYR were 180 kg/ha at TC, XG, and ZS, and 120 and 90 kg/ha at JH and CD, respectively. The optimal N application rates for late rice in the MLRYR were 150 kg/ha at TC, XG, JH, and ZS, and 90 kg/ha at CD (Fig. S5). In general, N applications need to be increased by 5.2% for early rice and reduced by 13.1% for late rice.

3.5.2. Optimal rice transplanting date at each station

The responses of rice yields to different transplanting dates in the NECP and in the MLRYR are shown in Fig. 9 and Fig. S6. The impacts of transplanting date shifts on yields for single rice in the NECP and late rice in the MLRYR were greater than those for single rice cultivation and early rice in the MLRYR (Fig. 9; Fig. S6). For single rice in the NECP, the rice yield changed with shifts in the transplanting date. It increased by up to 13.5% when the transplanting date was advanced by 10 d, while it decreased by up to 16.9% when the transplanting date was delayed by 10 d (Fig. 9). For single rice in the MLRYR, the yield did not significantly change with shifts in the transplanting date. When the transplanting date changed in the window from 10 d earlier to 10 d later than the observed transplanting date, the average yield change was < 5% (Fig. 9). The impact of transplanting date on early rice yield was not obvious except for at JH and CD, while for late rice yield, the decrease was obvious and became more variable when the transplanting date was delayed (Fig. S6). For early and late rice in the MLRYR, the yields increased by up to 7.5% and 6.3%, respectively, when the transplanting date was advanced by 10 d, while they decreased by up to 9.6% and 14.8%, respectively, when the transplanting date was delayed by 10 d. In general, the rice yield increased with earlier transplanting dates under current agronomic management practices, while it decreased with later transplanting dates for both single rice and double rice.

There were significant interactions between transplanting date and cultivar. For the optimal cultivars, yield varied greatly with changes in transplanting dates (Fig. 10). At WC, using optimal cultivars and the current transplanting date, single rice yields could increase by 26.4%, compared with the current observed yield, as shown in the Section 3.4.

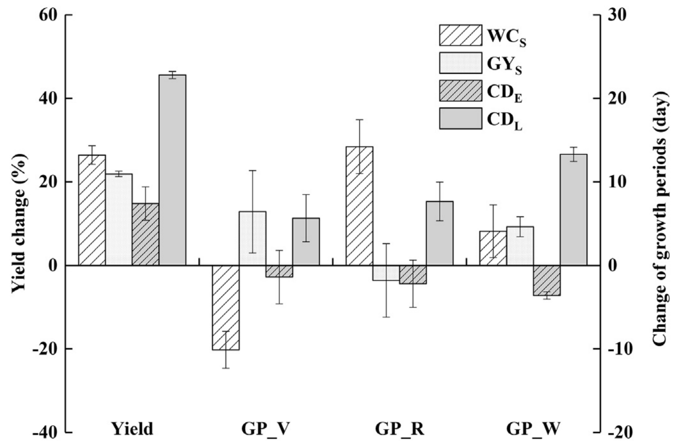

Fig. 7. Expected changes in yields and growth durations using the optimal five rice cultivars compared with the current cultivars at three stations (WC, GY, CD). GP_V: Days from transplanting to heading; GP_R: Days from heading to maturity; GP_W: Days from transplanting to maturity. The subscripts represent the cropping system; single rice, S; early rice, E; and late rice, L.

If the transplanting date was advanced by 10 d, then the yield could increase by 34.5% owing to the longer vegetative growth period. If the transplanting date was delayed by 10 d, then the yield could increase by 20.0%. For single rice at GY and late rice at CD, using the optimal cultivars, if the transplanting date was advanced by 10 d, then the yields could increase by 29.2% and 68.9% compared with current observed yields, respectively. For early rice at CD, the yield could increase by 46.1% compared with the current observed yield at the current transplanting date and the maturity date was delayed (i.e., simulation scenario 3 in Fig. 2). For double rice cultivation, if the transplanting dates of both early and late rice were advanced by 10 d (i.e., simulation scenario 7 in Fig. 2), the double rice yields could increase by 46.1% in comparison with the current observed yields, mainly owing to the earlier transplanting date of the late rice.

4. Discussion

4.1. Reasons underlying rice yield gaps in different regions

Rice potential yield showed an increasing or unchanged trend in the NECP and a declining or unchanged trend in the MLRYR from 1981 to 2009, which were attributed to climate changes. The results are consistent with some previous studies using different models and methods (Tao et al., 2013; Zhang et al., 2016). Over the past few decades,

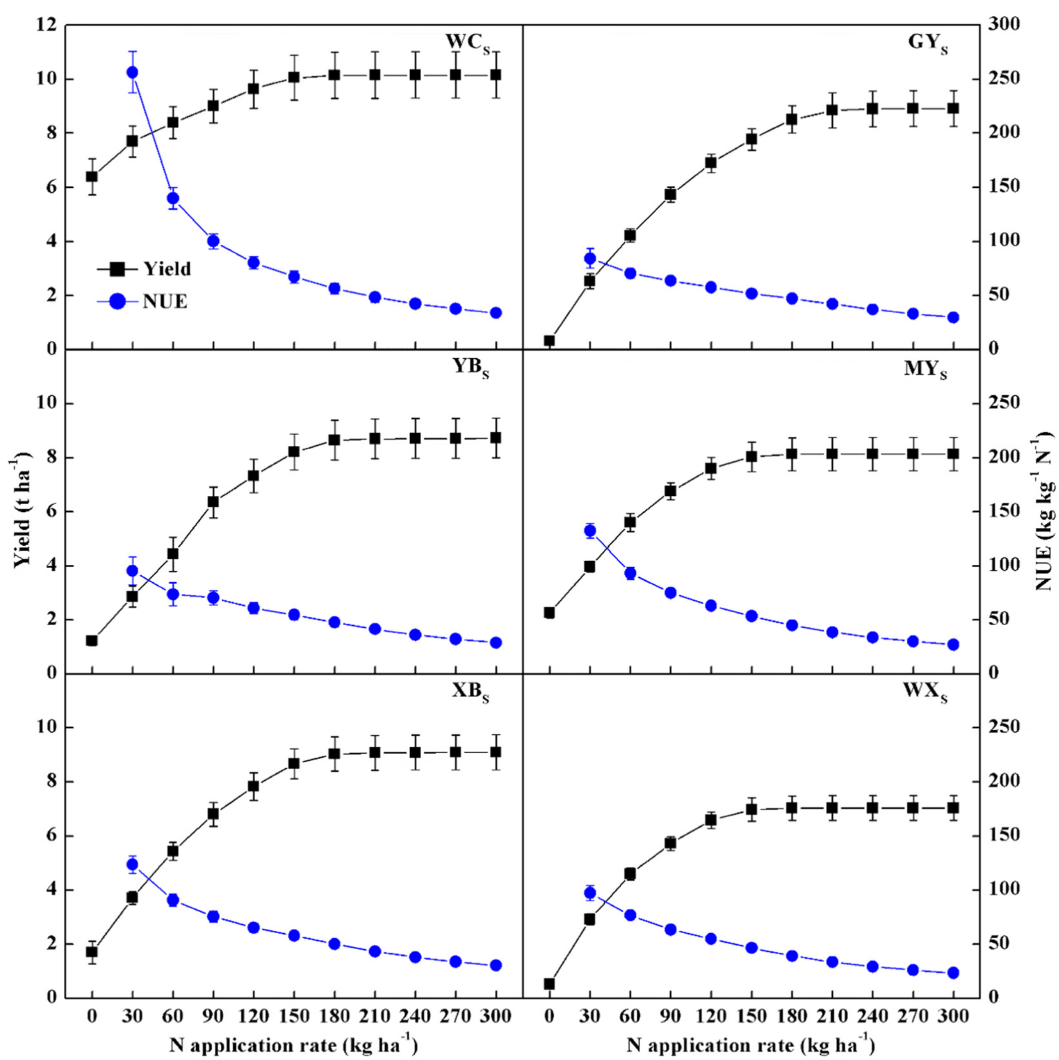

Fig. 8. Changes in rice yields and nitrogen use efficiencies (NUEs) with N application rates for single rice at three stations in the NECP (WC, YB, and XB) and three stations in the MLRYR (GY, MY, and WX). The subscript 'S' represents single rice.

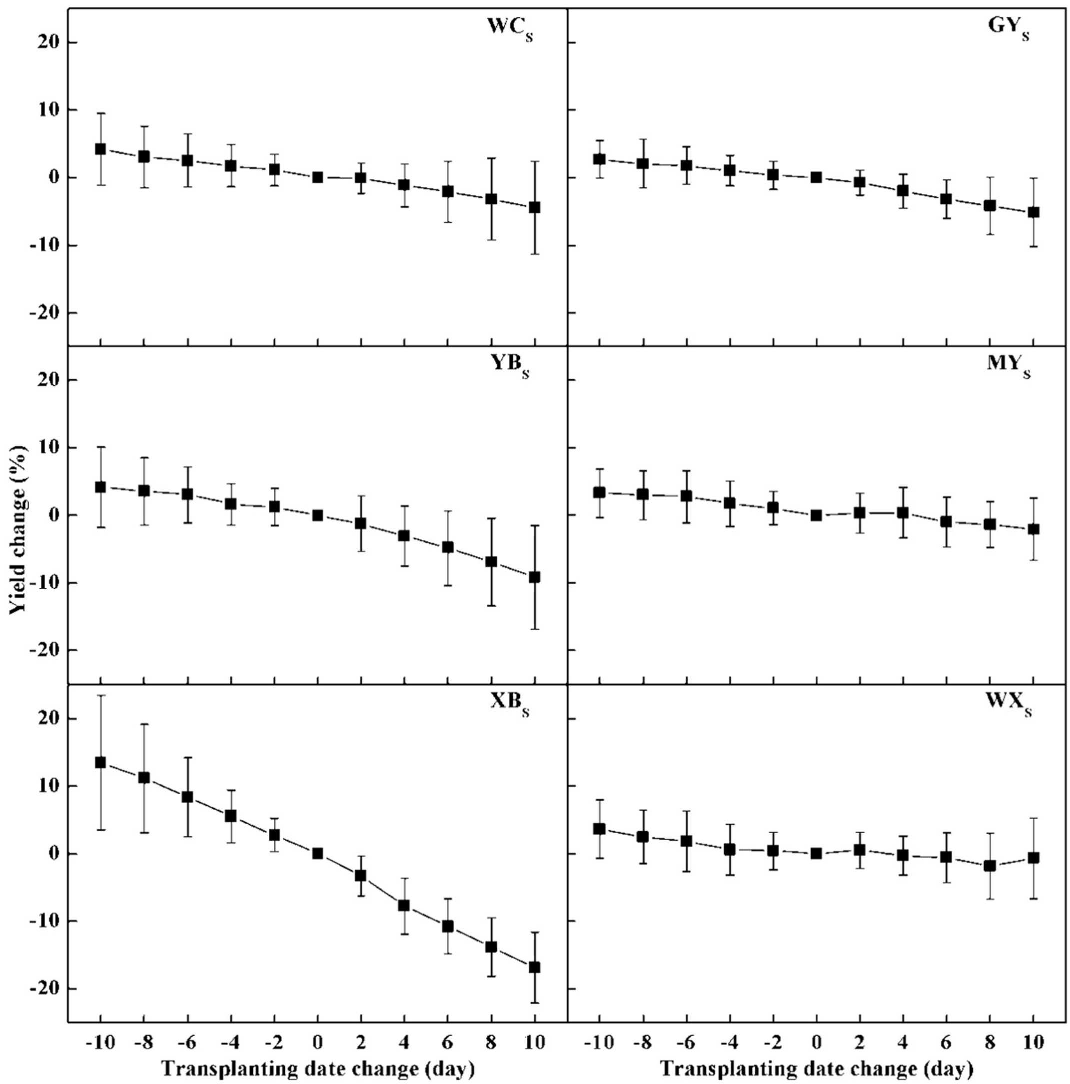

Fig. 9. Changes in rice yields with shifts in the transplanting dates at three stations in the NECP (WC, YB, and XB) and three stations in the MLRYR (GY, MY, and WX) with single rice cultivation. The subscript 'S' represents single rice.

climatic warming has reduced cold damage (Sun and Huang, 2011), increased photosynthesis rates, and had positive impacts on the rice yield in the NECP (Tao et al., 2008b). The NECP has a large potential for rice production improvement where rice yield potential and yield gap are increasing, and yield gap is relatively large. By contrast, the decrease in solar radiation and increased probability of heat stress with climatic warming are main reasons for the potential yield decrease in most of areas of the MLRYR (Chen et al., 2017; Zhang et al., 2014a, 2016). High-temperature stress could result in sterile or low-fertility pollen at the anthesis stage, resulting in an increase in blighted grains and a decrease in grain yield (Jagadish et al., 2007; Matsui et al., 1997).

The average rice yield gap among the different regions was 16.0% in 2000s. The yield gap was 28.9% for single rice in the NECP and 13.4% in the MLRYR. These estimates of yield gaps are generally comparable with some previous estimates. For example, the rice yield gap was estimated to be 27.3% in the NECP (Zhang et al., 2014b) and 10%–30% generally across the MLRYR (Chen et al., 2017). However, it was estimated to be 41.4% of the attainable yield in the NECP using a different rice model and census yield data at the county level by Wang et al. (2018). Yield gaps vary in different rice cultivation regions. They were mainly caused by water and nutrient stresses, as well as the negative impacts of weeds and insect pests. It is difficult to conduct calibration and validation experiments for water-limited yield and N-limited potential yield, which may produce uncertainty, because of data availability. Nevertheless, many previous studies have also shown that the CERES–Rice model can simulate the potential yield of rice under non-limiting nutrient (mainly N fertilizer) and water environmental conditions (Jones et al., 2003). Both water and N stresses were the limiting factors for rice in the NECP, while water stress was the main limiting factor in the MLRYR. Although the N fertilizer application rate in China is relatively excessive (Ju et al., 2009), regional disparities in overuse and underuse exist (Wang et al., 2011). The N application rate was deficient in the NECP and excessive in the MLRYR, which corroborated previous studies (Li et al., 2013; Wang et al., 2011). Rice productivity is vulnerable to water stress and increasingly subjected to drought in the MLRYR (Wang et al., 2014). The droughts can be caused by an uneven seasonal precipitation distribution, temporary seasonal drought, deficit irrigation or the inability of roots to absorb water. Owing to alterations in rainfall patterns and a shortened growth period cause by climatic warming, decreases in overall and irrigation-related water use efficiencies will occur in the future (Wang et al., 2014). Therefore, it is important for future research to improve water use efficiency and NUE without rice yield reductions in different regions. The yield gap shrank mainly because of the increase in the actual yield, while the potential yield changed slightly, which was consistent with previous studies (Chen et al., 2017; Wang et al., 2018; Zhang et al.,

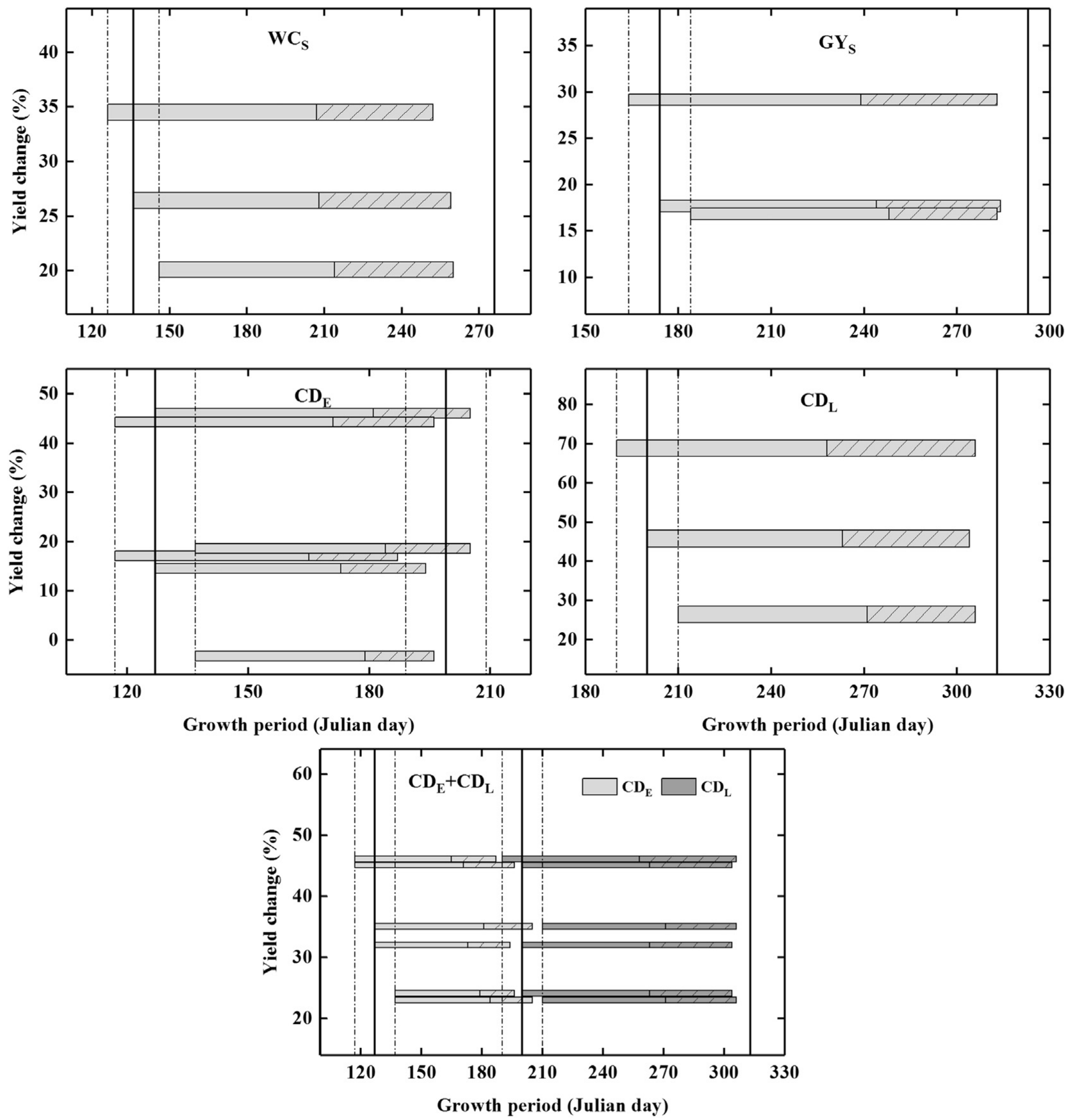

Fig. 10. Changes in rice yields using optimal cultivars with different transplanting dates at three stations (WC, GY, and CD). The vertical solid line indicates the current boundary of the growing season. The nearby two dotted lines represent transplanting date' ranges (± 10 d). The simulation scenarios for early rice and double rice at CD are shown in Fig. 2. The gray bars indicate the vegetative growth periods, and the gray bars with diagonal lines indicate the reproductive growth periods. The subscripts represent the cropping system; single rice, S; early rice, E; and late rice, L.

2014b). The actual yield increased notably owing to genetic advancements and improvements in agronomic management practices over the past decades in the major rice production regions (Peng et al., 2009). At some stations, such as MY and XG, rice actual yields have approached potential yields in recent years, suggesting that water and nutrients at these stations already meet the requirements of rice growth. To further increase potential yield and actual production, high-yielding cultivars that are more suitable to future climate conditions should be developed, and optimal cultivation and management practices employed.

4.2. Optimizing cultivars and improving agronomic management practices in different regions

Crop models, such as CERES–Rice, are useful tools to optimize the interactions between genotype, environment, and management. Using the CERES–Rice model, a full set of sustainable intensification options, including cultivar selection, water and N applications, shifts in transplanting dates, and cropping system optimization for specific environments, was proposed. These options can be expected to improve adaptability, water use efficiency and NUE, and produce more rice at a lower environmental cost. The current popular N application rate is ~150–250 kg/ha in the main rice production regions of China (Fan et al., 2007; Hu et al., 2007; Ju et al., 2009; Peng et al., 2006). Our suggested optimal N application rates, which ranged from 150 to 180 kg/ha on average, are supported by previous studies (Bai and Tao, 2017; Wang et al., 2011). To achieve greater productivity with a higher NUE, the N application rates used at the experimental stations should be increased by 47.5% and 21.7% for single rice in the NECP and MLRYR, respectively, increased slightly, by 5.2%, for early rice in the MLRYR, and decreased by 13.1% for late rice in the MLRYR. The results are supported by those of Wang et al. (2011) which showed that the N application rate should be reduced by ~15% in N-rich regions and increased by ~13% in N-poor regions.

The cultivars could be further improved to increase potential yields and, consequently, actual yields. Improved rice cultivars usually have greater potential yields (Peng et al., 2008; Takai et al., 2006). The optimal cultivars were characterized by longer growth durations, greater spikelet numbers, and greater grain weights. Longer growth durations allow rice plants to intercept more solar radiation and, therefore, increases photosynthesis, biomass and yield (Pal et al.,

2017). The durations for the vegetative and reproductive growth periods could also be optimized for different regions. These desirable traits are targets for selecting cultivars to grow at the present time and also for breeding future cultivars. Although there might be limited yield gains even if the current cultivars' grain numbers and grain weights are maximized, it is important to maintain these traits while improving others.

The impacts of transplanting date shifts on yield were greater for single rice in the NECP and late rice in the MLRYR than for single rice and early rice in the MLRYR. Shifts in the transplanting date can affect growth duration and climatic conditions during the growing season (Hu et al., 2017; Zhao et al., 2016). Rice transplanting dates should be advanced as far as possible in a suitable transplanting window to allow the extension of the reproductive growth periods for single rice and late rice, and to make full use of the improved climatic conditions resulting from climatic warming (Hu et al., 2017). Therefore, the interactions between genotype, environment, and management should be well optimized to propose the optimal genotype and management practice for a target environment, and to design and adjust the cropping system. As shown in this study, through the combined use of optimal cultivars and advanced transplanting dates, rice yields could increase more significantly than using either of the two parameters independently. Delays in transplanting dates will increase the risk of frost damage for single rice and late rice (Tao et al., 2013).

5. Conclusion

Using detailed field trial data at 11 agro-meteorological experimental stations in the major rice production regions of China and the crop model CERES–Rice, we found that actual rice yields were approaching potential yields in recent years, with an average yield gap of 16.0%. Both water and N stresses were limiting factors for rice in the NECP, while water stress was the main limiting factor for rice in the MLRYR. N application rates should be increased for single rice in the NECP and in the MLRYR; however, they should be reduced for late rice in the MLRYR. Early transplanting was beneficial to the yield, while late transplanting could reduce the yield. The cultivars with longer growth durations and greater spikelet numbers and grain weights are promising. The optimal cultivars, together with early transplanting, could improve the rice yield significantly by 29.2% to 68.9%. The application of a proposed full set of sustainable intensification options, which optimize the interactions between genotype, environment, and management, is promising. Once popularized, they will have the potential to increase resource use efficiency, producing more rice at a lower environmental cost. Our findings are useful to develop climate-resilient cultivars and optimal agronomic management practices for location-specific environments to increase potential yields and close yield gaps, and to accelerate sustainable agricultural intensifications. Furthermore, the study demonstrated the ability of advanced approaches to determine the scope of yield improvement, to identify the limiting factors, and to optimize the interactions between genotype, environment, and management. These ideas and approaches can be applied to other cropping systems and regions.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2019.01.007.

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